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LCA FOR ENERGY SYSTEMS

Life cycle assessment of light-emitting diode downlight luminaire—a case study

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Abstract
Purpose Light-emitting diode (LED) technology is increasingly being used for general lighting. Thus, it is timely to study the environmental impacts of LED products. No life cycle assessments (LCA) of recessed LED downlight luminaires exist in the literature, and only a few assessments of any type of LED light source (component, lamp and luminaire) are available.
Methods The LCA of a recessed LED downlight luminaire was conducted by using the data from the luminaire manufacturer, laboratory measurements, industry experts and literature. The assessment was conducted using SimaPro LCA software. EcoInvent and European Reference Life Cycle Database were used as the databases. The LCA included a range of environmental impacts in order to obtain a broad overview. The functional unit of the LCA was one luminaire used for 50,000 h. In addition, the sensitivity of the environmental impacts to the life was studied by assessing the LED downlight luminaire of 36,000 h and 15,000 h useful life and to the used energy sources by calculating the environmental impacts using two average energy mixes: French and European.
Results and discussion The environmental impacts of the LED luminaire were mostly dominated by the energy consumption of the use. However, manufacturing caused approximately 23 % of the environmental impacts, on average. The environmental impacts of manufacturing were mainly due to the driver, LED array and aluminium parts. The installation, transport and end of life had nearly no effect on the total life cycle impacts, except for the end of life in hazardous waste. The life cycle environmental impacts were found to be sensitive to the life of the luminaire. The change from the French to the European average energy mix in use resulted to an even clearer dominance of the use stage.
Conclusions The case study showed that the environmental impacts of the LED downlight luminaire were dominated by the use-stage energy consumption, especially in the case of the European energy mix in use. Luminous efficacy is, thus, a relatively appropriate environmental indicator of the luminaire. As LED technology possesses generally higher luminous efficacy compared to conventional ones, the LED luminaire is considered to represent an environmentally friendly lighting technology. However, data gaps exist in the data in LED product manufacturing and its environmental impacts. The environmental impacts of different LED products need to be analysed in order to be able to precisely compare the LED technology to the conventional lighting technologies.

Keywords Environmental impact · Life cycle assessment · Light-emitting diode · Light source · Lighting · Luminaire

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1 Introduction

It is estimated that lighting consumes approximately 19 % of the global electricity production (IEA 2006). Globally, the electrical lighting is provided mainly (62 %) by fluorescent lighting, including fluorescent and compact fluorescent

lamps (CFL) (IEA 2006). In contrast, the share of light-emitting diode (LED) in general lighting is low; LED lighting was estimated to cover 6.2 % of the general lighting in the European Union in 2010 (EC 2011). However, the market penetration of LED technology is rapidly increasing not only in the decorative lighting of coloured, usually low-power applications but also in general lighting.

The LED light sources represent a relatively new technology. In addition to the indicator and decorative lighting, there are LED lamps and luminaires on the market that possess sufficient luminous flux to be used in general lighting and even in high-power outdoor lighting. The challenges in the heat transfer from the chip through the heat sink have hindered the wider use of the LED technology. Efficient heat transfer is essential in order to slow depreciation of the luminous flux in LED light sources and, thus, realise long life.

There is no exhaustive studies on the environmental aspects of LED products, yet some studies exist. The United States Department of Energy (DOE) has published reports on the energy analysis and life cycle environmental impacts of LED die and LED lamp manufacturing (US DOE 2012a; 2012b). Lim et al. (2011) studied the material contents of indicator LED components of different colours by leachability tests. However, it concerns only the LED components of through-hole technology (THT) and not the LED lamp or luminaire as a whole. Dale et al. (2011) studied four different streetlight technologies, one of which was a LED luminaire. The study compared one-to-one replacement of high pressure sodium lamp luminaire to the metal halide, induction or LED lamp luminaire. It did not take into account the luminous flux or the standards and recommendations for street lighting. In addition, the ballasts and drivers were estimated to be similar and, thus, excluded from the assessment. The LED luminaire was found to have the lowest environmental impacts that were similar with the ones of the induction lamp luminaire. Navigant Consulting Europe Ltd. (2009) examined several energy-efficient light sources including an integrally ballasted LED lamp (12 W, 720 lm) and a LED luminaire (18 W, 1,170 lm). The life cycle environmental impacts of a LED lamp have also been compared to incandescent and CFL (Osram 2009; Quirk 2009, US DOE 2012b). The conclusion of the assessments are generally that LED and CFL lamps possess roughly the environmental impacts of the same scale and that the future LED lamp will be more environmentally friendly than the CFL, since no major technological development are expected in the CFL technology.

The environmental performance of the light source is dependent on the luminous efficacy if the analysis uses a proper functional unit taking into account the amount of light produced. The luminous efficacy of the incandescent lamp is low, typically 10–15 lm/W, while the one of CFL ranges approximately between 40 and 70 lm/W including the ballast, and fluorescent lamps (T5) up to approximately 100 lm/W including the ballast. The luminous efficacy of LED lamps has a wide range, approximately between 20 and 120 lm/W (Aalto University 2010). The LED chip luminous efficacy has well exceeded 200 lm/W in laboratories. In contrast to the LED technology, no major improvements are expected in the development of the conventional light source technologies, such as incandescent or fluorescent lamp technology. In addition, the lamp technologies of low energy efficiency are being banned in many regions, e.g., the inefficient incandescent lamps and high pressure mercury lamps in the European Union.

This study introduces the life cycle assessment (LCA) of a LED luminaire. It is a case study of one type of recessed downlight luminaire and does not represent the LED technology as a whole. Yet, it is an exemplary case. Currently, there are LED lamps and luminaires of varying properties available on the market. Notable differences are found in the properties among LED light sources concerning, e.g., the luminous flux and electrical properties such as harmonic distortion, colour temperature, colour rendering, colour shift and lumen maintenance.

2 Life cycle assessment of light-emitting diode luminaire

The environmental impacts of a LED luminaire were studied in an LCA. The LCA was conducted for a LED downlight luminaire in Fig. 1. The LED luminaire in question is a high-quality luminaire used in commercial and retail applications, in which it is intended to replace downlight luminaire equipped with two CFLs. The nominal electrical power of the LED luminaire is 19 W. The product contains the driver and the LED luminaire including all its parts, such as the heatsink, reflector, high-power blue LED components on a circuit board and a “remote phosphor” plastic diffuser, which external surface is coated with a thin layer of luminophores. The LCA is conducted according to the international standards ISO 14040 (2006) and ISO 14044 (2006) and a French standard NF P01-010 (2004). The SimaPro version 7.3.2 was used as the LCA software (PRé Consultants 2012).

2.1 Goal and scope definition

The goal of this LCA is to study the environmental impacts of a LED downlight luminaire and to determine the life cycle stages and material and energy inputs that cause the greatest impacts. In addition, how sensitive the environmental impacts are to the life of the luminaire and to the energy mix of the use stage is determined.

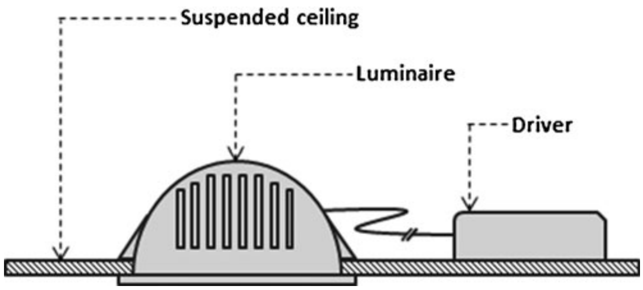


Fig. 1 Simplified diagram of the LED downlight luminaire

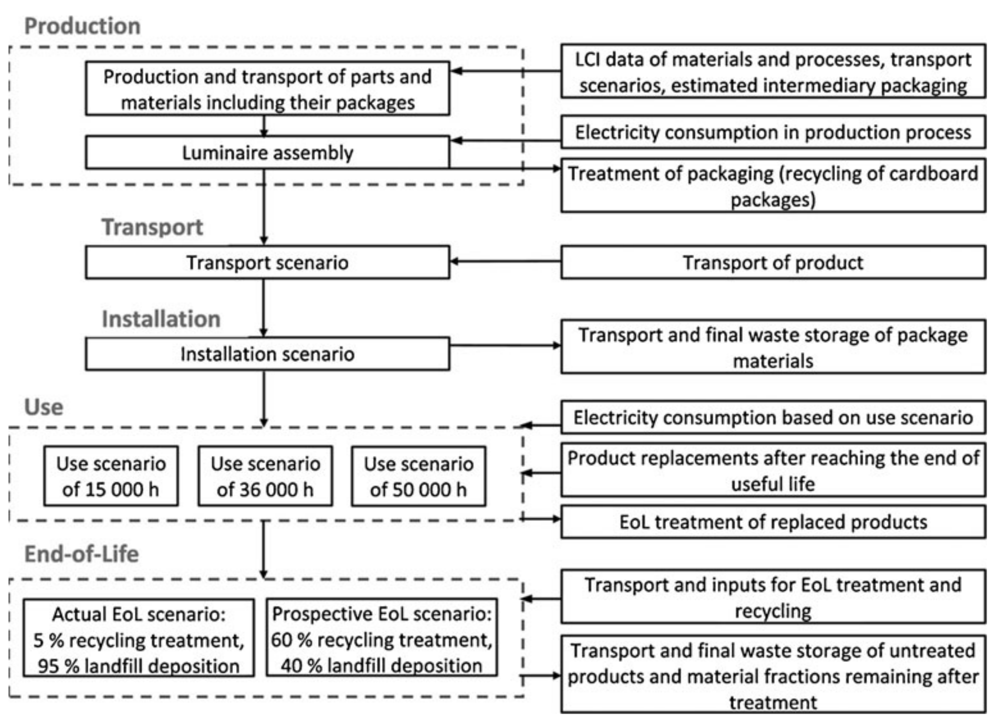
The LCA includes the manufacturing, transport, installation, use and end-of-life (EoL) stages (Fig. 2). The system boundaries exclude the lighting, heating and cleaning of the factories; administrative work; transport of the employees; tool manufacturing; infrastructure; and transport infrastructure, such as building and maintenance of roads. The study excluded also the inputs that represented less than 2 % of the total weight of the product and for which there were no life cycle inventory available, according to the rules of the French standard NF P01-010.

The functional unit is the use of the 19-W LED downlight luminaire including the driver during 50,000 h and producing 1,140 lm of light with colour rendering index R_a of approximately 80. All the electrical and photometric characteristics were measured by the Centre Scientifique et Technique du Bâtiment (CSTB) lighting laboratory (Martinsons 2009a, 2010), and the life is based on the information from the manufacturer, since life tests are still in progress at CSTB. The measured luminous efficacy is approximately 60 lm/W.

Since the life of the luminaire is a crucial factor in the LCA, its impact is studied more profoundly. The life of the LED products is allegedly long but there are concerns regarding its realisation. In addition, the development of the LED technology is so rapid that the replacement of the product to an up-to-date device may occur before the end of the product technical life. The life of the LED downlight luminaire is 50,000 h according to the manufacturer. A life of 50,000 h is a somewhat general approximation for LED luminaires but it is not possible to carry out burning tests of such a long life. The life of the ballast is considered in the LCA to be the same as the life of the luminaire, since it is sold as one unit and the ballast will be replaced together with the rest of the luminaire. At the end of the operating life, the luminaire is expected to provide less than 70 % of initial luminous flux taking into account both the lumen depreciation and product failures.

The life of 50,000 h is used as a base case scenario in the LCA. The base case is compared to the lives of 36,000 h and 15,000 h. On the basis of the LM-80 (IESNA 2008) method, the 36,000 h life was chosen. The method states that the life of the LED packages and modules shall be estimated based on a burning test of a minimum of 6,000 h. It is recommended to extrapolate the life of the LED package or module based on the burning test only up to six times the test period, i.e., in the case of 6,000 h test, until 36,000 h. It is noted that LM-80 does not apply to LED luminaires as a whole but it was used, nevertheless, due to the lack of a specific method for LED luminaires. Although 15,000 h life is somewhat shorter than the service life of LED products, it was

Fig. 2 Stages of the life cycle included in the LCA of the LED luminaire



estimated to represent the case where the replacement would be triggered by obsolescence instead of technical end of life of the product. For instance, lighting fixtures may be updated in high-quality commercial shops due to the technology improvement and the urge to maintain the modern look of the lighting. The replacement may occur as frequently as every 2 to 4 years. The annual use of lighting is 5,000 h in retail buildings according to EN 15193 (2007). Thus, 15,000 h useful life equals to 3 years of use. In these cases, the replacement rate is related to the choices of the end-user than to the technical performance of the product.

Six scenarios of the product system were chosen to analyse the impact of the product life and the EoL scenario:

1. Luminaire life 15,000 h (four products needed during 50,000 h), current recycling scenario in the EoL
2. Luminaire life 15,000 h (four products needed during 50,000 h), prospective recycling scenario in the EoL
3. Luminaire life 36,000 h (two products needed during 50,000 h), current recycling scenario in the EoL
4. Luminaire life 36,000 h (two products needed during 50,000 h), prospective recycling scenario in the EoL
5. Luminaire life 50,000 h (one product needed during 50,000 h), current recycling scenario in the EoL
6. Luminaire life 50,000 h (one product needed during 50,000 h), prospective recycling scenario in the EoL.

In addition to the life of the luminaire, the annual environmental impacts are dependent on the use scenario. The annual operating hours are not included in the LCA but only the total life is considered. However, the annual environmental impacts depend on the annual operating hours. The annual operating hours vary according to the use of the space but are approximately, e.g., 2,500 h/year in offices and 5,000 h/year in hotels and retail facilities (EN 15193).

2.2 Life cycle inventory analysis

2.2.1 Manufacturing

The manufacturing stage comprises the raw material acquisition of all parts of the luminaire installed in the beginning of the operating life. The manufacturing of the replacement luminaires, in case of the useful life shorter than 50,000 h, is modelled in the use stage according to the NF P01-010 (2004).

Table 1 lists the material and process inputs of the LED downlight luminaire manufacturing. The driver data was retrieved by dismantling the driver and identifying the components. All driver parts include an additional 2 % mass to take into account the material losses during manufacturing. The printed circuit board (PCB) is modelled as a two-sided board that includes the mounting processes (50 % THT and 50 % surface-mount technology (SMT)). THT components were weighed, while the weight data of the SMT components was retrieved from the component datasheets and ZVEI documents (ZVEI 2012). The remote phosphor has recently been the subject of a French Luminosurf research project. In this project, CSTB conducted LCAs on several types of organic and inorganic luminophores used in LED lighting (Pradal et al. 2012; Martinsons 2009b). The luminaire assembly process is modelled on the basis of the energy consumption provided by the luminaire manufacturer: approximately 0.03 kWh of electricity per luminaire. The amount of electricity covers only the assembly process and no other energy consumption of the luminaire factory.

The LED components were modelled as 5-mm LED components for information and communication technology found

Table 1 Raw material and process inputs of the LED downlight luminaire manufacturing

Part	Raw material, product, or process input	Amount
Driver	PCB, 2-sided, 50 % SMT, 50 % THT, lead-free, including mounting processes	0.009 m^2
	Capacitors (electrolyte, film, or unspecified)	18 g
	Diodes	0.6 g
	Resistors	2 g
	Transformers	48 g
	Integrated circuits	0.1 g
	Transistors	0.3 g
	Other components (active, passive, or unspecified)	0.7 g
	Steel	4 g
	Plastics	130 g
	Connectors (65 % nylon 66, 27 % copper, 7 % iron, 1 % tin)	5 g
LED array	Light-emitting diodes (16 pcs.)	28 g
	Silicone product; thermoforming	3.74 g
	Aluminium	23 g
Aluminium parts	Aluminium (heatsink and reflector), processing	700 g
	Coating	0.17 m^2
Other parts	Steel	17 g
	Plastics; injection moulding	26 g
	Cable	7 g
	Paper	3 g
Remote phosphor cover	YAG (yttrium aluminium garnet) coating	0.2 g
	Electricity, French mix	0.002 kWh
	Aluminium oxide	0.1 g
	Organic chemicals	0.1 g
	Plastics, injection moulding	7 g
Assembly	Electricity, French mix	0.029 kWh
Waste treatment (packaging)	Recycling of the intermediary cardboard packages	175 g

in the EcoInvent database in which the particular data was from year 2007 (Ecoinvent 2010). However, it is estimated that the diode in the database, a THT component, results to low environmental impacts compared to the actual SMT LED component. Thus, on the basis of the estimations by industry experts, the weight of the SMT LEDs is multiplied by a factor of 5 in order to take into account the underestimation in the component data. Yet, it is acknowledged that a more accurate and up-to-date life cycle data is needed regarding the LED components used currently in general lighting.

Transport of parts is included in each part accordingly, a total of approximately 2 tkm by lorry and 12 tkm by trans-oceanic freight. Likewise, packaging is taken into account and modelled in each part. Packaging is modelled mainly as cardboard that accounts for approximately 10 % of the weight of the product parts if precise data was unavailable. The cardboard used in the packaging of the luminaire parts is estimated to total 114 g and the package of the final product 210 g. The waste treatment in the manufacturing stage covers the transport and recycling of the cardboard packages.

2.2.2 Transport

Transport stage includes the transport from the manufacturer site to the place it is used. Transport data was gathered from the luminaire manufacturer, and when such data was not available, the default scenarios for the product environmental profile (PEP) (Association P.E.P. 2011) were used as reference. In PEP, the global transport is estimated to be 19,000 km by ship and 1,000 km by lorry, the intercontinental transport 3,500 km by lorry, and local transport 1,000 km by lorry.

2.2.3 Installation

The installation of the luminaire considers the transport and the final storage of the package materials. The transport is modelled as 30 km by lorry. The final waste disposal is modelled as municipal solid waste deposition.

2.2.4 Use

The use of the luminaire is modelled on the basis of the energy consumption. The downlight luminaire consumes 19 W/h. The average French energy mix is used for electricity production. The French electricity is modelled to be produced by nuclear power (77 %), hydropower (12 %), coal (4 %), natural gas (3 %) and oil (1 %), and imported (2 %) (Ecoinvent 2010). The sensitivity assessment uses average European energy mix (30 % nuclear power, 28 % coal, 19 % natural gas, 16 % hydropower, 4 % oil and 2 % wind power) (Ecoinvent 2010). In addition to the energy consumption during operation, the use stage includes the manufacturing of replacement luminaires in case of a useful life shorter than 50,000 h.

2.2.5 End of Life

On the basis of the information from the French lamp recycling organisation Recylum, two EoL scenarios of the LED luminaire were created: current and prospective treatment scenarios. The current scenario is estimated at 95 % of landfill and 5 % of recycling treatment, while the prospective scenario includes 40 % of landfill and 60 % of recycling treatment. The landfill disposal takes into account the transport of the waste and the deposition on the landfill. In addition to the recycling of the metal parts and the disposal of other fractions, the recycling treatment includes the transport of the product from the point of use to the collection point and the corresponding material fractions to the storage centre and, finally, to the treatment centre. The recycling of the metal parts is modelled as aluminium recycling (95 %) and the rest (5 %) is disposed as hazardous waste. Other parts of the luminaire are disposed as municipal solid waste.

2.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) introduces the environmental impact categories and calculation methods used in the LCA. EcoInvent and European Reference Life Cycle Database were used as databases in the LCIA (Ecoinvent 2010; EC, JRC 2008). This assessment uses the MatFrance method, version 2.03, which is based on a French standard NF P01-010 (2004) and AIMCC (2009). The NF P01-010 is not compulsory but it is widely used in the environmental assessments in the building sector in France. The environmental impact categories are introduced in Table 2. It is mainly based on CML 2001 method (Guinée et al. 2002) but contains some differences, e.g., the photochemical ozone creation potential takes into account only the hydrocarbons (NF P01-010 2004). The eutrophication potential is excluded from NF P01-010, and it is described in XP P01-010-3 (2009).

3 Results

The environmental impacts of the manufacturing of a LED downlight luminaire were divided between the driver, LED package, aluminium parts, remote phosphor, luminaire assembly process, waste treatment of the packaging materials, and other materials (Fig. 3). The LED components and the circuit board they are attached to, i.e., the LED array, accounted for 3 % of the total weight of the luminaire, while their environmental impact ranged between 4 % and 50 %, depending on the impact category. The aluminium parts,

Table 2 Environmental impact categories chosen for the LCA of LED downlight luminaire. CFC-11 refers to trichlorofluoromethane

Environmental impact category	Abbreviation	Method	Unit (eq.)
Primary energy	PE	NF P01-010	MJ
Renewable energy	RE	NF P01-010	MJ
Non-renewable energy	NRE	NF P01-010	MJ
Abiotic depletion potential	ADP	NF P01-010	kg Sb eq.
Water consumption	WaC	NF P01-010	l
Hazardous waste	HW	NF P01-010	kg
Non-hazardous waste	NHW	NF P01-010	kg
Inert waste	IW	NF P01-010	kg
Radioactive waste	RW	NF P01-010	kg
Global warming potential	GWP	NF P01-010	kg CO_2 eq.
Acidification potential	AP	NF P01-010	kg SO_2 eq.
Air pollution	AiP	NF P01-010	m^3
Water pollution	WaP	NF P01-010	m^3
Ozone depletion potential	ODP	NF P01-010	kg CFC-11 eq.
Photochemical ozone creation potential	POCP	NF P01-010	kg C_2H_4 eq.
Eutrophication potential	EP	XP P01-020	kg PO_4 eq.

eq. equivalent

such as the heatsink, accounted for 11–42 % of the environmental impacts. The environmental impacts of the driver ranged between 19 % and 66 %. The PCB of the driver has a notable share in most environmental impact categories, but otherwise, the environmental impacts of the driver are scattered across a number of parts. The most critical parts of the driver are the electrolyte capacitors in inert waste and ozone depletion, unspecified capacitors in water pollution and photochemical ozone creation, steel in water consumption and glass diodes in photochemical ozone creation and hazardous waste.

The comparison in Fig. 4 presents three cases of life of the product (15,000 h, 36,000 h and the base case 50,000 h) and two EoL cases (actual and prospective). The average environmental impact of the base case was 34 % (2–70 %) lower compared to the case of 15,000 h useful life, while the 36,000 h case resulted to 23 % (1–47 %) lower average impacts compared to the 15,000 h case. The total life cycle environmental impacts were almost independent from the EoL scenario. The total life cycle primary energy consumption per the functional unit was approximately 13,070 MJ in the base case, 13,410 MJ in the case of 36,000 h useful life and 14,080 MJ in the case of 15,000 h useful life. Respectively, the global warming potential (GWP) impact resulted to 112 kg, 130 kg and 167 kg CO_2 equivalent.

Figure 5 shows the environmental impacts of the life cycle divided into manufacturing, transport, installation and use. The use is divided into two parts: energy consumption, and the manufacturing and transport of the replacement luminaires. Figure 5 excludes the EoL. Only one luminaire of 50,000-h life is needed for the functional unit (see Fig. 5a), while two luminaires of 36,000-h life (see Fig. 5b) or four luminaires of 15,000-h life (see Fig. 5c) are needed to provide light for 50,000 h. The manufacturing of the initial product caused approximately 23 % (0.7–79 %) of the environmental impacts in the base case, whereas the manufacturing of the initial product and the replacement products altogether created approximately 33 % and 45 % of the environmental impacts in the case of 36,000 h and 15,000 h useful life, respectively.

Figure 6 illustrates the division of the environmental impacts to the life cycle stages when an average French or European energy mix is used in the use stage. The French energy mix in use stage results to approximately 30 % lower

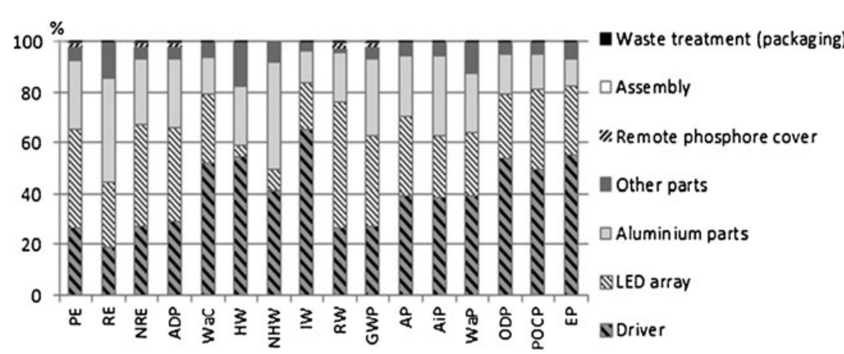


Fig. 3 Division of the environmental impacts of the manufacturing stage of the LED downlight luminaire

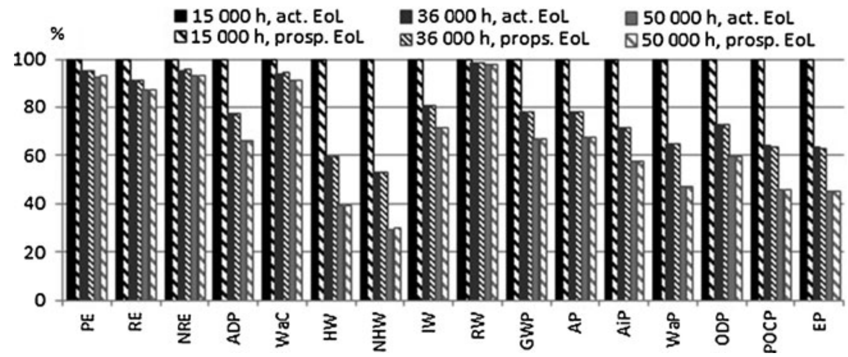


Fig. 4 Comparison of the life cycle environmental impacts of LED downlight luminaire in three scenarios of product life (15,000 h, 36,000 h, 50,000 h) and two end-of-life scenarios (act. = actual scenario of 95 % landfill, 5 % recycling; prosp. = prospective scenario of 40 % landfill, 60 % recycling)

environmental impacts in 12 out of 16 impact categories. The European mix causes lower impacts in the categories of primary energy, non-renewable energy, water consumption and radioactive waste, mainly due to its lower share of nuclear power compared to the French mix.

Figure 7 shows that the environmental impacts are divided differently to life cycle stages depending on the use-stage energy mix. When the use is modelled by using the French mix, the manufacturing accounts for approximately 22 % and use 76 % of the life cycle impacts, while the European mix in use stage divides the impacts between manufacturing (7 %) and use (93 %).

3.1 Uncertainties

Despite the efforts put in this LCA case, uncertainties and data gaps exist in the assessment. It was not possible to model all inputs of the luminaire life cycle or to obtain representative data of each input. There was no life cycle data available on the LED chip used in general lighting but it was estimated on the basis of an indicator LED. The environmental impacts are sensitive to the life of the luminaire luminaire and to the use-stage energy mix. In addition, this LCA case study concerns only one example of a LED downlight luminaire, and the LED luminaire product range is vast.

4 Discussion

The environmental impacts of the LED luminaire vary by environmental category. The use-stage energy consumption was found out to account for the majority of the environmental impacts in case of 50,000 life of the luminaire in all impact categories except for the non-hazardous and hazardous waste categories. In these two categories, the manufacturing accounted for 78 % and 38 %, and EoL 1 % and 28 %

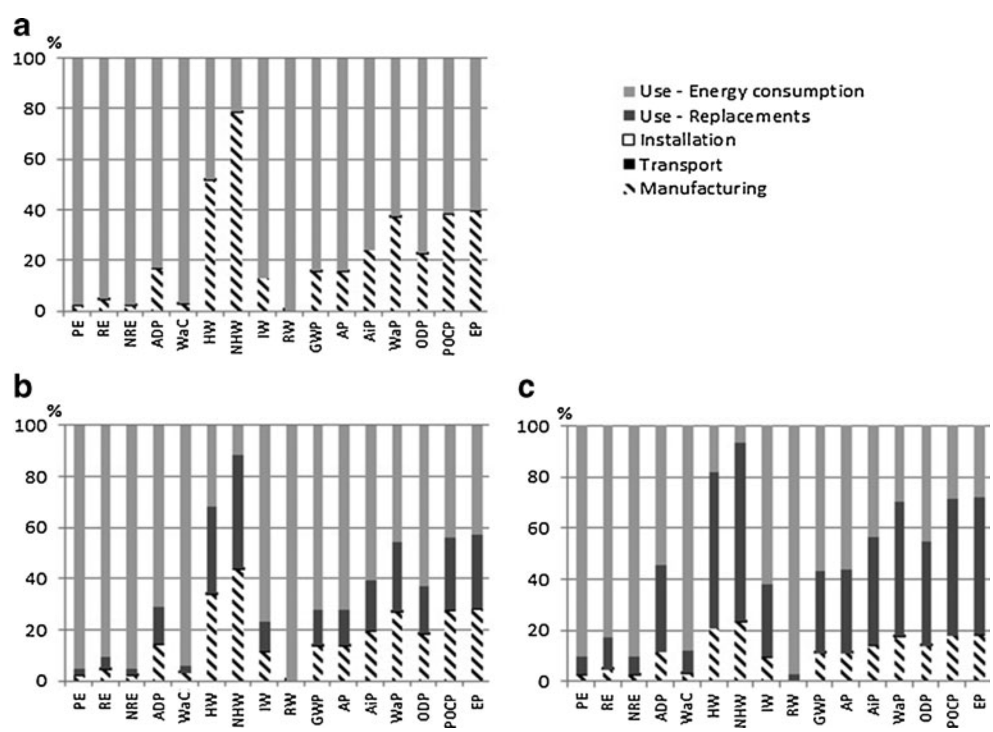


Fig. 5 Division of environmental impacts into life cycle stages when the life of the LED downlight luminaire is **a** 50,000 h, **b** 36,000 h, and **c** 15,000 h. EoL is excluded

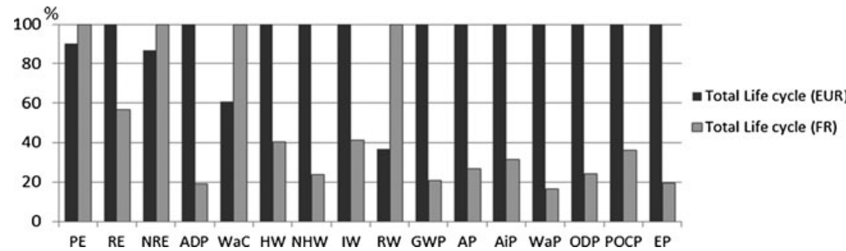


Fig. 6 Total life cycle environmental impacts using European or French average energy mix in the use stage

of the total life cycle impacts, respectively. The high percentages of manufacturing in these waste categories are mainly due to the driver and aluminium parts. The EoL had very little to no effect on the total life cycle impacts due to the dominance of use and manufacturing stages, except in hazardous waste impact. Yet, the benefits of proper recycling of the LED luminaires, in general, are recommended to be subjected to a more profound study.

The environmental impacts of the manufacturing stage are divided mainly between the LED driver, LED array and aluminium parts, which cover together over 80 % of the manufacturing impacts in each impact category. However, there is uncertainty in the life cycle inventory data of the LED component: the LCA was conducted using an estimation of an indicator LED to correspond to the LED component by a weight factor of five. Contradictory information has been published on the correlation between the environmental impacts of the indicator LED and a high-power LED component: a US DOE (2012b) report collects thoroughly the material and energy inputs of the manufacturing processes of a LED. It states that the environmental impacts of a high-power LED component represent approximately 94.5 % lower environmental impacts than the 5-mm indicator LED in the EcoInvent database. However, while the US DOE report compared the LED components on the basis of the luminous flux (4 lm to 100 lm), the LCA on the LED downlight luminaire considered the weight of the component, not the luminous flux, as the EcoInvent data was available on weight basis. With these notably different results and methods of comparison, it is clear that more studies and data are needed in order to conclude the environmental impacts of LED products, whether in terms of the weight or luminous flux of the LED component.

The manufacturing efforts of the LED product cannot be neglected in an LCA. It is implied that the manufacturing may account for a notable share of the environmental impacts, even though its importance depends on the use-stage energy source. A US DOE (2012a) study estimates the manufacturing process energy consumption to range between 0.1 % and 27 % of the total life cycle energy consumption of a LED lamp. Another US DOE (2012b) report calculated that the raw materials used in manufacturing caused on the average 16.8 % of the total life cycle impacts of a LED lamp.

The life of the LED luminaire affects the environmental impacts and their division between the life cycle stages. The luminaire of the nominal life of 50,000 h causes approximately 34 % lower total environmental impacts compared to the case in which the luminaire had useful life of 15,000 h. The manufacturing of the LED luminaire causes on the average 23 % of the life cycle impacts in the case of 50,000 h life, while the share of the manufacturing of the initial and replacement products is increased to 33 % in the case of 36,000 h life and to 45 % in the case of 15,000 h life. Yet, there is significant variation in the sensitivity to the life among the impact categories.

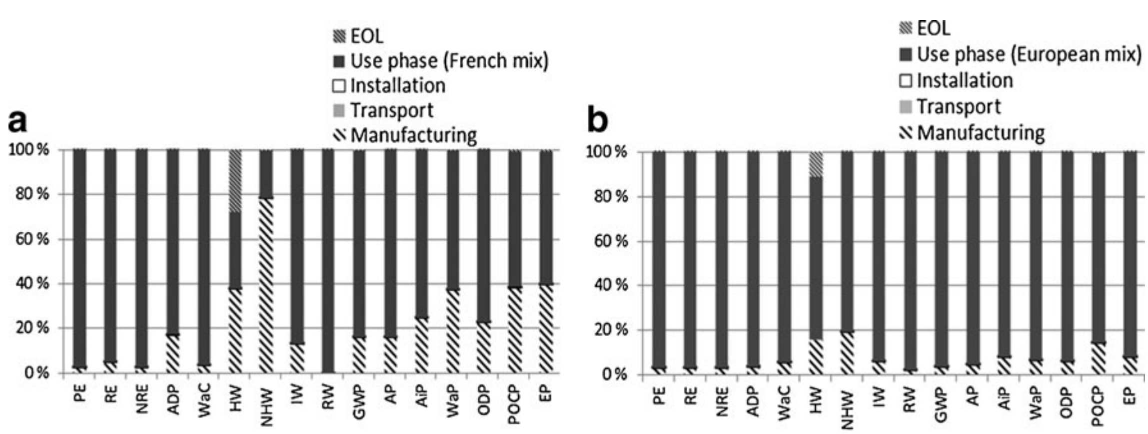


Fig. 7 Division of environmental impacts into life cycle stages when the energy consumption during use is modelled as **a** average French and **b** average European electricity production mix

The life cycle of the luminaire resulted to primary energy consumption of 13,070 MJ and GWP of 112 kg CO_2 per functional unit (50,000 h use of the luminaire producing 1,140 lm). Several previous LCAs of light sources use lumen hours as the functional unit. The LED downlight luminaire of 50,000 h life consumed approximately 230 MJ primary energy and caused 2.0 kg CO_2 emissions per 1 M lmh.

Such a LED downlight luminaire has not been subjected to an LCA before. It is not possible to accurately compare this LCA to the ones of LED lamps or LED luminaires of different purposes and LCA boundaries. However, the LCA results show that the use-stage energy consumption is dominant but also that the manufacturing cannot be neglected, especially in the case of a short or moderate useful life.

5 Conclusions

The environmental impacts of the LED downlight luminaire in the case study were generally dominated by the energy consumption in the use stage. The dominance was even clearer when the European energy mix was used. Thus, it confirms the use of luminous efficacy of a light source as an environmental indicator. However, the results show that the manufacturing efforts cannot be neglected in the LCA of the LED luminaire. Yet, it is acknowledged that there are uncertainties in the LCA calculations, notably in the modelling of the LED components.

The assessment is sensitive to the energy mix in use and the useful life. The importance of the manufacturing stage will be further increased when the energy production is shifted to the less-polluting energy production. In contrast, the importance of the manufacturing stage will be reduced as the life of the LED products becomes longer. Longer product life will cause lower total environmental impacts, as seen in the comparison of 50,000 h, 36,000 h and 15,000 h life. However, a balance should be found when the replacement should take place from the point of view of the environmental impacts, the improved product quality, and the costs of the replacement.

The results showed that the EoL treatment had nearly no impact from the total life cycle point of view. In the case of cleaner energy production, the significance of the EoL stage may increase. The recycling of the LED luminaire may increase along with the increase of the collection and treatment targets of the waste electrical and electronic equipment.

Further studies are suggested to include a wide range of LED products. In case of comparing light sources of different shapes and sizes, the functional unit needs to be appropriate and recommendably consider the luminous flux. It is also advised to analyse the sensitivity of the LCA to the used energy source and to the life of the product. In addition, the future total sustainability studies should consider the fast increase of the luminous flux and the decrease of the costs of the LED products.

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